MARINE PHYSICAL LABORATORY
of the Scripps Institution of Oceanography
San Diego, California 92132

A LARGE APERTURE ACOUSTIC ARRAY TO OBSERVE OCEANIC DENSITY

FINAL REPORT

G. Thomas Kaye

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ABSTRACT

A large aperture, planar hydrophone array, with sound source, has been constructed and operated by the Marine Physical Laboratory. The Scattering Array (SCAR) is being used as a remote sensing device to observe the density distribution in the oceanic water column. The array of 128 elements is towed to sea, submerged and suspended from a surface vessel. Real-time digital array phasing will allow discrimination between specular reflection (density layering) and point scatterers (biota).

INTRODUCTION

Knowledge of small-scale density features in the oceanic water column has grown substantially within the past decade. Prior to this period, the vertical density structure, that was inferred by observations with Nansen bottle casts and bathythermographs, was assumed to be one of well-mixed transition between various water types.

With the advent of the Salinity-Temperature- Depth (STD) and the Conductivity-Temperature- Depth (CTD) measurement systems density features, with vertical wavelengths on the order of meters, were observed which altered the concept of well-mixed transition zones. Instead, there appeared to be layers of well-mixed water, with each layer having a different density. At the boundaries of these layers, there were sheets approximately one meter thick where the density changed abruptly from one layer to another.

An even more sensitive measurement system was designed by M. C. Gregg and C. S. Cox of Scripps Institution of Oceanography (SIO). This free-falling vehicle allowed resolution of vertical density features with wavelengths as small as 2 cm. Their observations have exhibited the great detail of the density profile of the water column. Numerous small-scale gravitational instabilities were observed which indicate that small-scale processes might be involved in the development of vertical density structure. Subsequently fluid dynamicists have performed laboratory experiments which might explain several ways in which small-scale density structure might evolve in the ocean.

Unfortunately the oceanic measurement systems have low sampling rates which do not allow resolution of the time scales of the evolution and destruction of small-scale density features. Are all of these observed features layered phenomena or could some of them be turbulent clouds where one water type is mixing with another? What is the lateral extent of these features? Do the features interact and, if so, how do they interact? These are some of the problems which must be answered before small-scale density features can be explained, and their effect upon sound propagation understood.

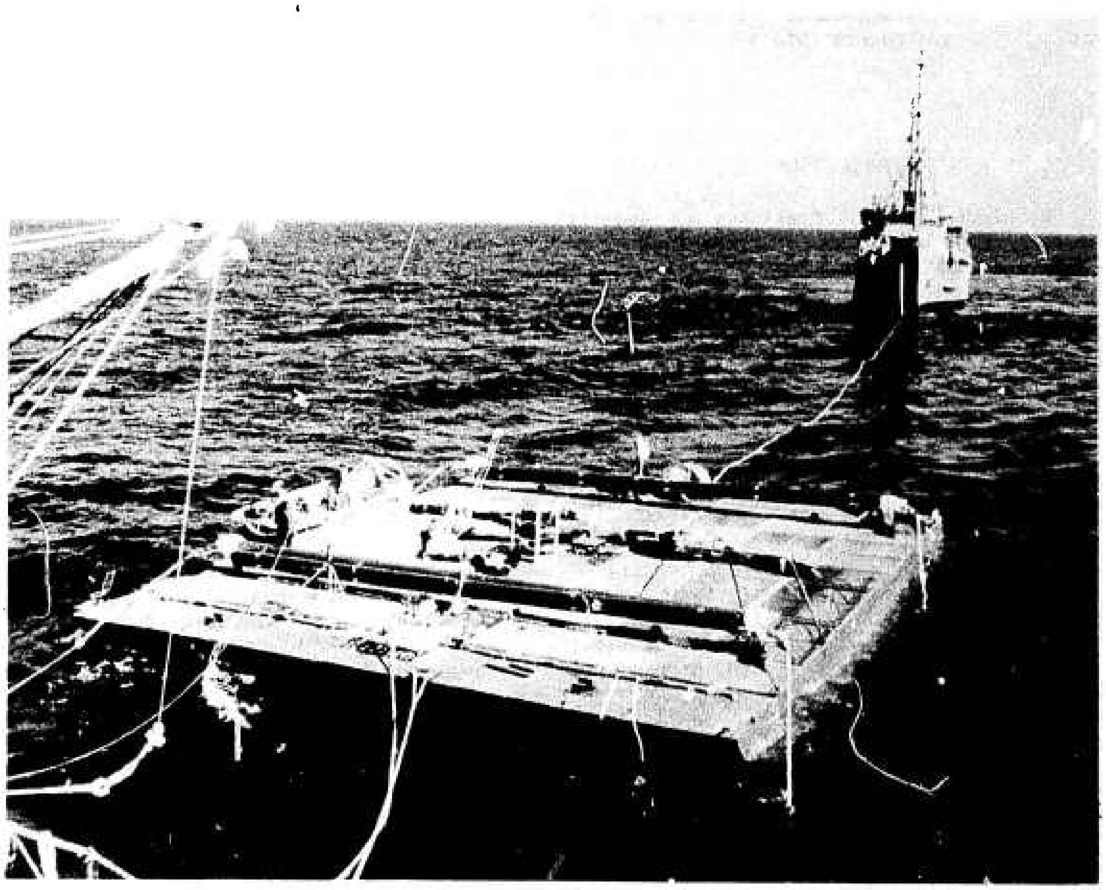
In order to begin to answer these problems, another measurement system, based upon a different sampling concept, was needed. Such a concept was suggested by W. H. Munk of SIO. He suggested that density strata be sampled indirectly, by analyzing the acoustic energy that was back-scattered by these

strata. An analagous measurement system using high-pulse beam radars has been employed by meteorologists to study atmospheric density features and shear layers. For a similar sonar application to the oceanic problem, V. C. Anderson of the Marine Physical Laboratory (MPL) of SIO defined the characteristics of the sonar array that would be needed.

With funding from the Advanced Research Projects Agency (ARPA), a Scattering Studies Group was formed from MPL personnel. The completed vehicle, the Scattering Array (SCAR), has been constructed and become operational. This publication is intended to provide some of the details of the construction and operation of the Scattering Array, (SCAR).

SCATTERING ARRAY HISTORY

Sep 1972	At-sea test of usefulness of high-frequency directional hydrophones.
Feb 1973	Prototype hydrophone element tested at sea. Test of 1/18 scale model of SCAR and ORB conducted in model basin of Offshore Technology Corporation.
Mar 1973	Contract let for manufacture of array modules.
May 1973	Completion of first design of beam-forming electronics.
Sep 1973	Arrival of array flotation modules.
Dec 1973	Completion of basic array assembly.
Mar 1974	Ashore array handling technique tested. Array maneuvered into and out of water.
Apr 1974	Completion of delivery and testing of hydrophones.
May 1974	Completion of at-sea array handling equipment.



Photograph 1. The Scattering Array (SCAR) with the Ocean Research Buoy (ORB) in the foreground and a surface support vessel in the background.

Jun 1974 Successful diving operations of array in 100 ft of water off the coast of San Diego.

Jul 1974 Installation of hydrophones, cabling cones and baffles. First interfacing between SCAR and electronics onboard ORB.

Aug 1974 First sea trial with complete system. Improvement of array handling equipment.

Dec 1974 Sea trial with complete system. Data collected.

SCATTERING ARRAY CHARACTERISTICS

Dimensions: 50 ft x 45 ft x 6 ft

Weight in air: Approximately 65 tons.

Array construction: Seven (7) separate flotation modules (dimensions 6 ft 2 in x 50 ft) joined by bolts.

Flotation: Fourteen (14) compartmentalized tanks, two per flotation module, fabricated of 26 in. diameter steel pipe. Upper tanks remain unflooded as permanent buoyancy. Lower tanks can be flooded and vented during array diving operations.

Sonar System

Source: Cylindrical piston transducer with conical reflector power - 8 kW; frequency range - 3.5 to 20 kHz; source level 122 [illegible]

Hydrophone array - 128 high-frequency directional hydrophones arranged around the source in roughly a plane circular array; bandwidth - 2 kHz.

Minimum sampling period: 5 sec

Minimum pulse duration: 1 cycle

Minimum vertical resolution: 30 cm

Signal-processing capability

Beamformer: For each depth range sampled 400 beams are electronically formed. 200 are focused to respond to returns from localized biological scatterers. 200 are focused for echoes from partially- reflecting microstructure planes.

Direct print-out of vertical beam information upon a recorder in a fathometer- type presentation.

Graphic display of formed beams for each depth range presented cyclically over 1000 depth ranges.

Magnetic tape storage of raw hydrophone data for on-shore processing.

Complementary Data

Pen-and-ink recording of temperature microstructure over a 100 ft depth range as sensed by a thermistor-pressure package. This package is alternately raised and lowered by a winch from the submerged Scattering Array.

Continuous pen-and-ink recording of water velocity at the depth of the Scattering Array.

Continuous pen-and-ink recordings of line tensions of suspension lines of Scattering Array.

Wind velocity recorded from sensors positioned above ORB.

XBT observations.

CONSTRUCTION OF THE ARRAY

The basic construction of the array is shown in Fig. 1. The vehicle is an assembly of seven separate modules, each of dimensions 6 ft 2 in. wide, 50 ft long, and 6 ft high. (See Photograph 2.) The modules were brought to the construction site and placed with a crane on three I-beams. These I-beams had been placed in a horizontal plane with a tolerance of ±1/8 in. Once on top of these beams, the modules were positioned with respect to one another and bolted together with 1-in. bolts. The modules are constructed of angled steel, with grating on the top and lattice of angled steel on the bottom. Within the bottom lattice, the hydrophones were positioned, aligned and bolted. The vertical sides of the barge were covered with thin steel plating to reduce the possibility of damage to the internal piping and cabling due to surface wave action.

Each module contains two flotation tanks, which were fabricated from 26-in. diameter steel pipe and are 42 ft in length. The tanks are positioned one above the other for stiffness. Each tank is compartmented into either five or six sections. The upper layer of tanks of the array are watertight and serve as the permanent buoyancy group of the array. The lower layer of tanks can be flooded and vented individually by module, providing maximum stability and control during

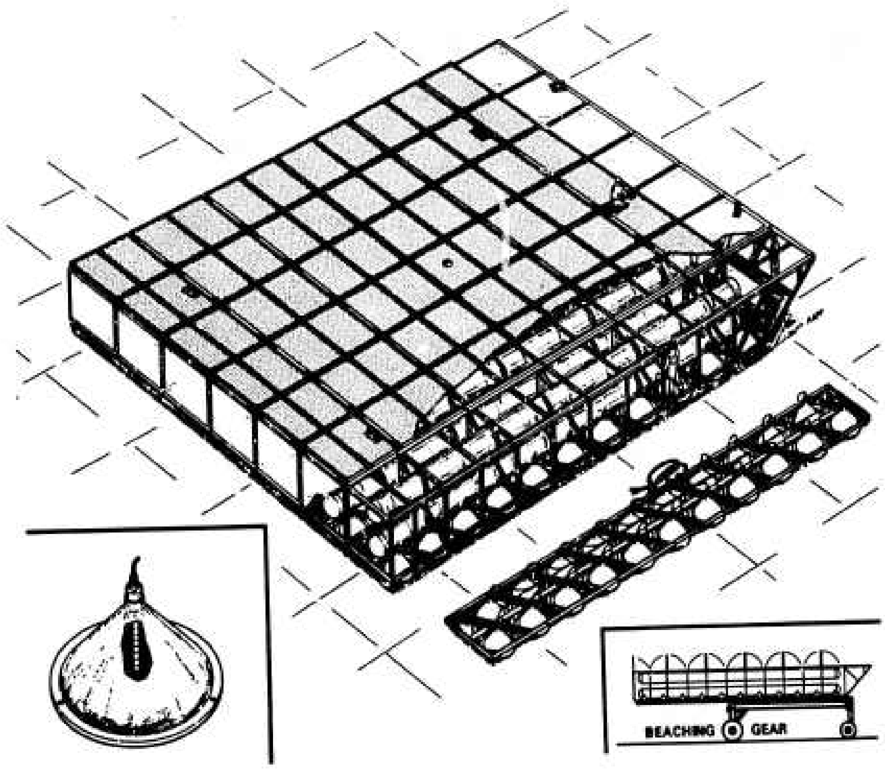
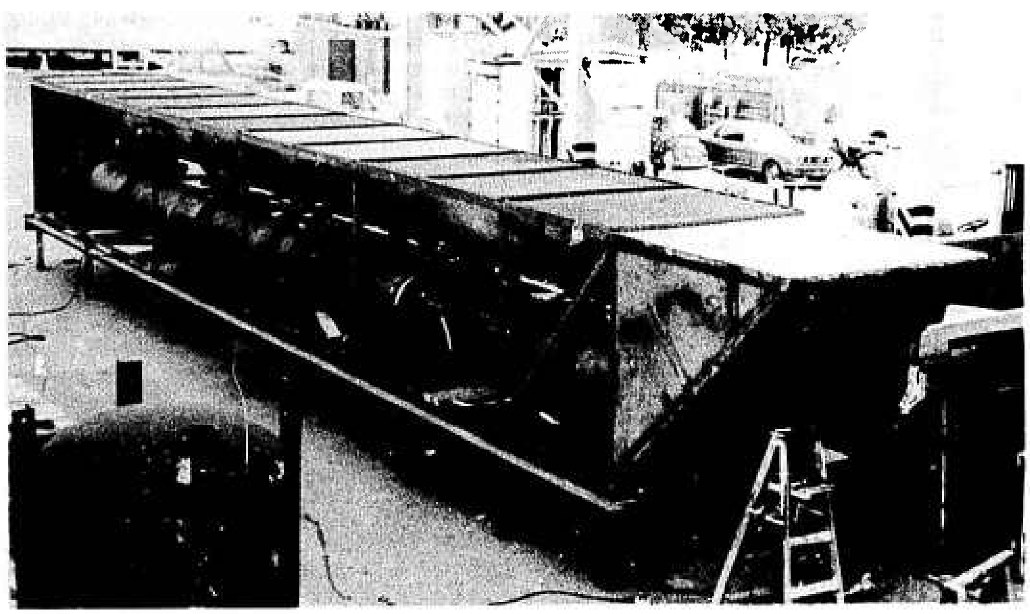


Figure 1. Artist's conception of construction of barge for the Scattering Array.



Photograph 2. One of the seven flotation modules that were bolted together to form the SCAR barge.

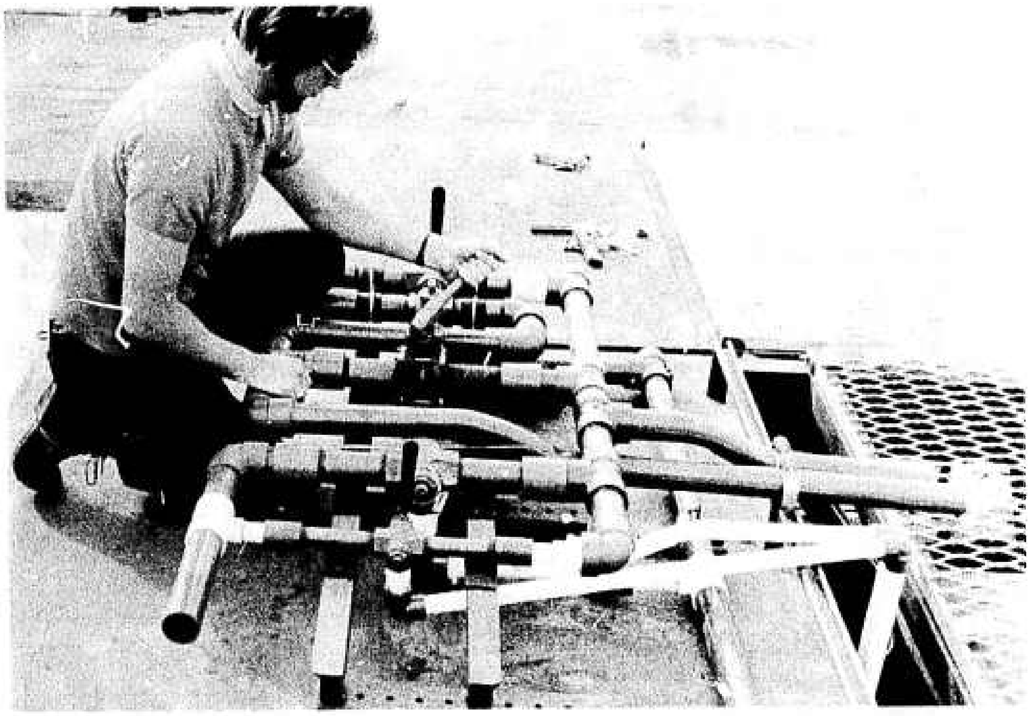
diving operations. Within this lower layer, the end two compartments of both ends of the outboard tanks can each be controlled independently. Thus, these eight compartments serve as a trim control of the array, whenever diving or submerged.

Pipes of 3-in. diameter, open to the water, extend down from the diving tanks at several points along the tanks. These pipes are linked to a single discharge point near the geometric center of individual units at the bottom plane of the array in order to prevent the development of unstable righting moments whenever flooding. The tanks are flooded by opening valves at the top forward ends of the tanks. The valve handles extend from the tanks to the top of the array, so that they can be easily manipulated by a diver underwater.

Flooding and blowing of the main diving tanks are achieved by two separate acts. First, the valves are placed in either the open or closed positions for, respectively, flooding and blowing. The second act is the opening or closing of the main control valves from a central position on the bow. See Photograph 3. The statuses of the trim tanks are controlled exclusively from this point. An appropriate valve system has been utilized to minimize "cross-talk" of venting between tanks. An umbilical air hose extends from an air compressor aboard the Ocean Research Buoy (ORB), the surface support vessel, to the manifold aboard the array. Air pressure is maintained at 30 psi over ambient by utilizing an air regulator valve which uses a sea pressure reference. Additionally, leakage detectors for each of 56 compartments in the permanent buoyancy tanks are monitored onboard ORB.

The weight in air of the array, when fully loaded, is approximately 65 tons. In spite of the large weight and the fact that the array is an assembly of seven modules, SCAR has demonstrated great rigidity during its sea trials.

On the December 1974 sea trip, the array was on the surface during a short storm with 35-kt winds and 10-ft seas. A post-storm inspection revealed minimal damage, so the experiment was continued, SCAR was submerged and data were collected.



Photograph 3. Diving control station on the array bow.

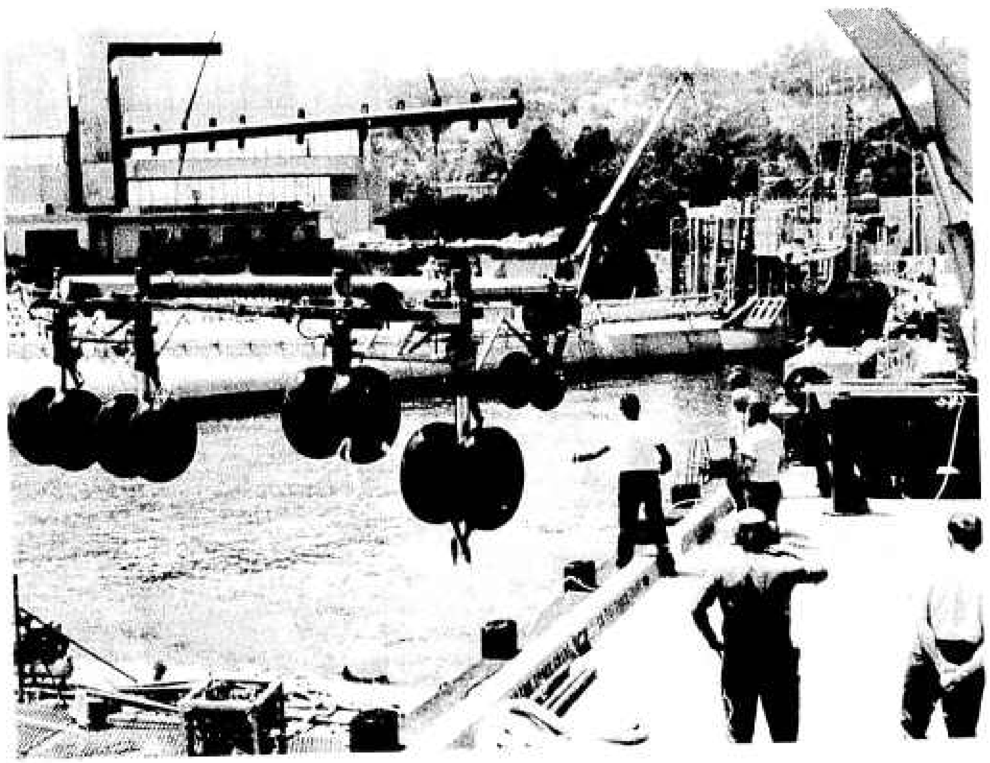
ASHORE ARRAY HANDLING SYSTEM

Whenever the array is not at sea, it is stored ashore in an area provided by the General Dynamics Corporation. Storage ashore limits fouling by harbor biota, which might reduce the acoustic effectiveness of SCAR. Additionally, array maintenance ashore is more convenient. This required that the array be portable, and, consequently, an ashore array handling system was designed and built by MPL personnel. The handling dolley, resembling a large boat trailer, was fashioned from available components of the beaching gear intended for the P6M jet seaplane, an abandoned project. The weight in air of the dolley is approximately 16,000 lbs; it has a negative buoyancy in sea water of approximately 1500 lbs.

With the array loaded aboard the dolley, the device is towed to a seaplane ramp and launched. After launching, the dolley is lowered from the array with the use of three hand winches positioned topside on the array. The services of divers and a crane allow the dolley to be recovered from the water and stored ashore, while the array is at sea. See Photograph 4. For beaching the array, this process is reversed.

SUSPENSION SYSTEM

The Scattering Array and the Ocean Research Buoy are towed to sea to the observation site. Normal towing speeds are 2-4 kts. After ORB is moored, SCAR is submerged to approximately 60 ft in depth and suspended from ORB by four suspension cables. Onboard ORB these cables are led over sheaves to winches. Above the array the cables are joined to 1 1/4-in. diameter nylon line. Onboard the array the lines are led into four compression spring devices.



Photograph 4. The carrying dolley is detached from SCAR and recovered for storage ashore, while the array is at sea.

Details of the compression spring devices are shown in Fig. 2. The bottom pipe, with a 12-in. diameter, is allowed to rotate within two collars. The collars are bolted to the array. Two of these large pipes are positioned athwartships, one forward and one aft. At the ends of the pipes, sheaves are attached, over which the nylon lines ride. Two compression spring tubes, 5 3/4 in. ID and 35 ft 10 in. long, are strapped on top of each 12-in. pipe. Within each tube are 25 springs. Between each two springs is a 1/2 in. washer in order to prevent one spring from working directly into another. Each washer is ringed with a polyethylene shoe and each tube is well lubricated to suppress the noise generated by spring movement.

The suspension line rides on the sheave, feeds into the spring tube, and passes through the 25 springs. The bitter end is fashioned around a thimble which abuts the last spring. Thus any increased suspension cable tension up to 3600 lbs per cable, should be compensated for by the compression of the springs. After the springs have been compressed, additional cable tension may be taken up, for short periods of time, by the elasticity of the nylon line for tensions up to 25,000 lbs per line. This compensation system allows for the decoupling of the array from the vertical motion of the surface support vessel.

This system was designed to compensate for vertical surface excurisons up to 10 ft in height. Whenever the array has been submerged to date, only small sea states have occurred, with maximum observed wave heights of 3 ft. However, divers on inspection tours have failed to discern any array movement. Pitch and roll instruments, mounted on the array, have indicated that the maximum bow movement observed was 4-in (10 cm). A set of accelerometers would be needed to monitor array movement more closely. The water mass entrapped by the scattering array is approximately

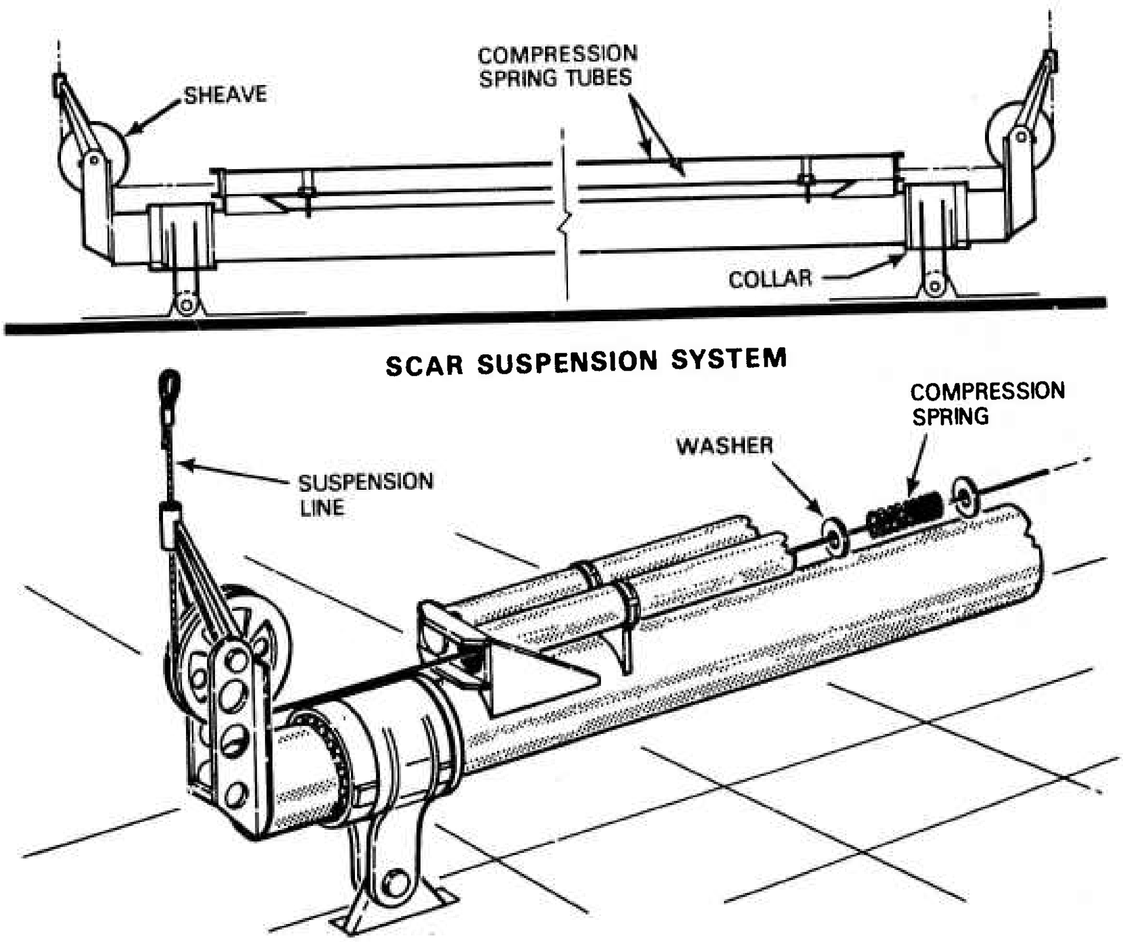


Figure 2. SCAR suspension system with cutaway showing the compression spring installation.

375 tons. It is felt that with this suspension system and because of the great inertia of the array and the entrapped water, that SCAR will usually be independent of sea surface motion.

To date one problem with this suspension system has occurred. A rough edge on one of the sheaves abraided the outer sheath of one suspension line. The problem was noticed by divers on an inspection dive. The array was surfaced, the line replaced, and the array submerged. After the sea trip the sheaves were smoothed and no significant line wear was observed on the subsequent sea trip. Diver inspections continue to be part of the at-sea routine.

Finally, it is desirable that the physical orientation of the array be within 1/2° of a horizontal plane, for data processing reasons. This orientation is monitored directly onboard ORB. Whenever the array orientation is out of bounds, it can be realigned either by adjusting the ballast in the trim tanks or by manipulating the suspension cable lengths with the winches aboard ORB. Utilizing this procedure an acceptable array orientation has been maintained.

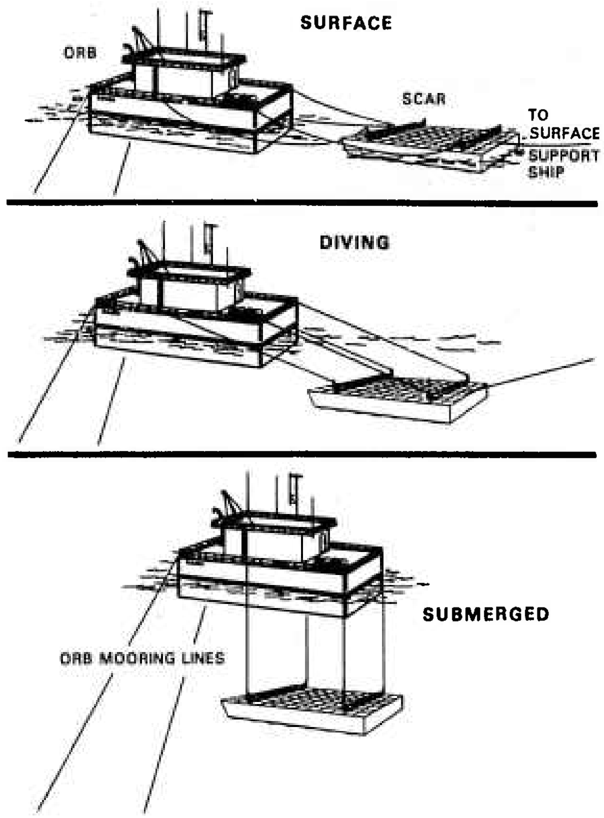


Figure 3. Diving procedure for the Scattering Array.

DIVING PROCEDURE

ORB is placed into a double mooring. See Fig. 3. Four suspension cables are led from winches aboard ORB to the compression spring devices aboard SCAR. Additionally a line goes from the stern of the array to a standby support vessel. The standby vessel provides a back tension on the array to keep SCAR away from ORB during diving operations.

Minimally two SCUBA divers are needed in order to dive the array. One diver is in charge of opening and closing the valves located on each flotation module. The other diver is positioned at the main control station on the bow. From this main control station, he can designate to the other diver which valves should be manipulated. After this the main control diver floods or blows the tanks with the control piping on the bow. Additionally he has direct control of the eight trim tanks.

The diving tanks are flooded sequentially from outboard to inboard, in order to avoid unstable righting moments. When all of the tanks but the central diving tank are flooded, the array is awash but still maintains its positive buoyancy. The diver at the control panel can then adjust the array trim, if necessary, to obtain a slight bow down angle, which aids in purging the flooded tanks of trapped air. Subsequently the array is submerged by flooding the central diving tank. Although the diving angle of the array is not critical, it is desirable to keep SCAR in a horizontal attitude as nearly as possible.

As SCAR submerges, back tension upon it is eased, allowing the vehicle to slip underneath ORB. At a depth of 70 ft, the negative buoyancy of the array is counteracted by ORB through the suspension system. Transition time between the flooding of the final tank and attaining the submerged position underneath ORB is around 5 min.

Once that transition has been completed, the array is raised to the observation depth, usually 50 ft, with the four suspension winches aboard ORB. After this, the amount of negative buoyancy of the entire array can be altered to ensure that suspension cable tensions will lie within the required range. Finally, alteration of the ballast in the trim tanks allows another readjustment to make the array horizontal. The array attitude is continuously recorded aboard ORB, so that deviations of the array from a horizontal plane can be noted and further ballast adjustments made if necessary. To date 16 cycles of diving and surfacing have been conducted.

SONAR SYSTEM HARDWARE

The source for the array is an Edo Western Model 415 transducer. It has a peak power of 8 kW and an operating frequency range of 3.5-20 kHz. The predicted source level for maximum input power is 122 dB. the beam pattern is 30° conical at -3 dB. This transducer has a mechanical Q of approximately 1, yielding the advantages of a fast rise time, and short ring time.

The passive portion of the array is an arrangement of 128 elements, which are in a circular plane around the source. This circle has a radius of nearly 22 ft. Each element consists of a highfrequency directional hydrophone and reflecting cone. The receiving sensitivity of all hydrophones was measured at 5 kHz and was required to be within the limits of -85 ±3 dB re 1 V/microbar. Each hydrophone stick is encapsulated in a ceramic cylinder of 1/8-in. thickness. The reflecting cones for the hydrophones were fabricated of 3/8-in. thick fiberglass and the insides of the cones are covered with neoprene rubber. Each cone has a base diameter of 40 3/4 in. and an apex angle of 90°.

During the installation of the elements, care was taken to ensure that all of the hydrophones were within the same horizontal plane. For correct signal phasing of the array, it is essential that the relative physical positions of the elements be accurately known. To accomplish this, the flotation modules were supported at several points with cribbing in order to minimize deformation of the module assembly. Then the elements were installed with the aid of a system utilizing a theodolite and water level. After installation all elements were checked and found to be within 3/16 in. of the array plane. The configuration is rechecked after each sea trip.

A separate cable is led from each hydrophone to a central point on top of the array. This hardwiring process required approximately 32,000 ft of hydrophone cable; however, the reliability gained by hardwiring each hydrophone to the surface vessel compensates for this drawback. The cables are bundled into one electrical umbilical cord for further connection to the beamforming electronics aboard ORB.

SIGNAL PROCESSOR

The beamforming system includes elements for: (1) sampling and storing hydrophone signals, (2) forming beam summations on the delayed and phased signals, and (3) displaying the results. Figure 4 is a system block diagram, showing the relationships among the two system computers and other elements of the processor. Two general purpose minicomputers are employed. A PDP-11 serves as the system control unit and is responsible primarily for the sequencing of operations. A Microdata 3200, a fast microprogrammable processor, calculates the delay and phase control parameters required for dynamically focusing the beamformer.

Each computer has a single bus structure in which the central processing unit (CPU), memory and input/output equipment are interconnected via a high speed, asynchronous data path. A bus interface unit provides a simple, flexible way of interconnecting the two buses. This interface unit allows the PDP-11 Unibus to access the memories and other devices that are attached to the 3200 Monobus. Data may be transferred in either direction, but are always under the control of either the PDP-11 processor or one of the Unibus peripheral controllers.

The system peripheral equipment is attached to the Unibus, while the beamformer processing units are connected to the Monobus. Peripherals include a fixed-head disc, a magnetic tape unit, a keyboard/printer, and two displays. A graphic recorder provides a multi-ping display of the largest signal return as a function of depth, with the data for the two focusing modes displayed side-by-side. Also, a color television display shows all the data for a single ping. The steering direction of the beam is indicated by raster position and the two focusing modes are distinguished by color. This display shows all of the information for a signal depth and then steps through the successive depths with similar presentations.

The fixed-head disc is used to reformat the beamformer output data and the magnetic tape unit provides archival storage of the raw hydrophone data. Thus these units provide the capabilities for playing the data back through the beamformer ashore, for more extensive data reduction.

In real-time operation, input data are loaded into the signal memory by the sampling control unit, a Monobus DMA controller. Information for selecting the properly delayed data for each hydrophone channel, and for phasing these samples for input to the beam summation unit, is calculated by the 3200 and stored in the steering control memory. Separate data paths connect this control information to the signal memory, and the signal memory output to the beam summation unit. The beam summation unit adds the complex data samples from all of the hydrophone channels and the 3200 provides the squared magnitude of the result to the 3200 which, in turn, stores the result for access by the disc and the PDP-11 graphic recorder control program.

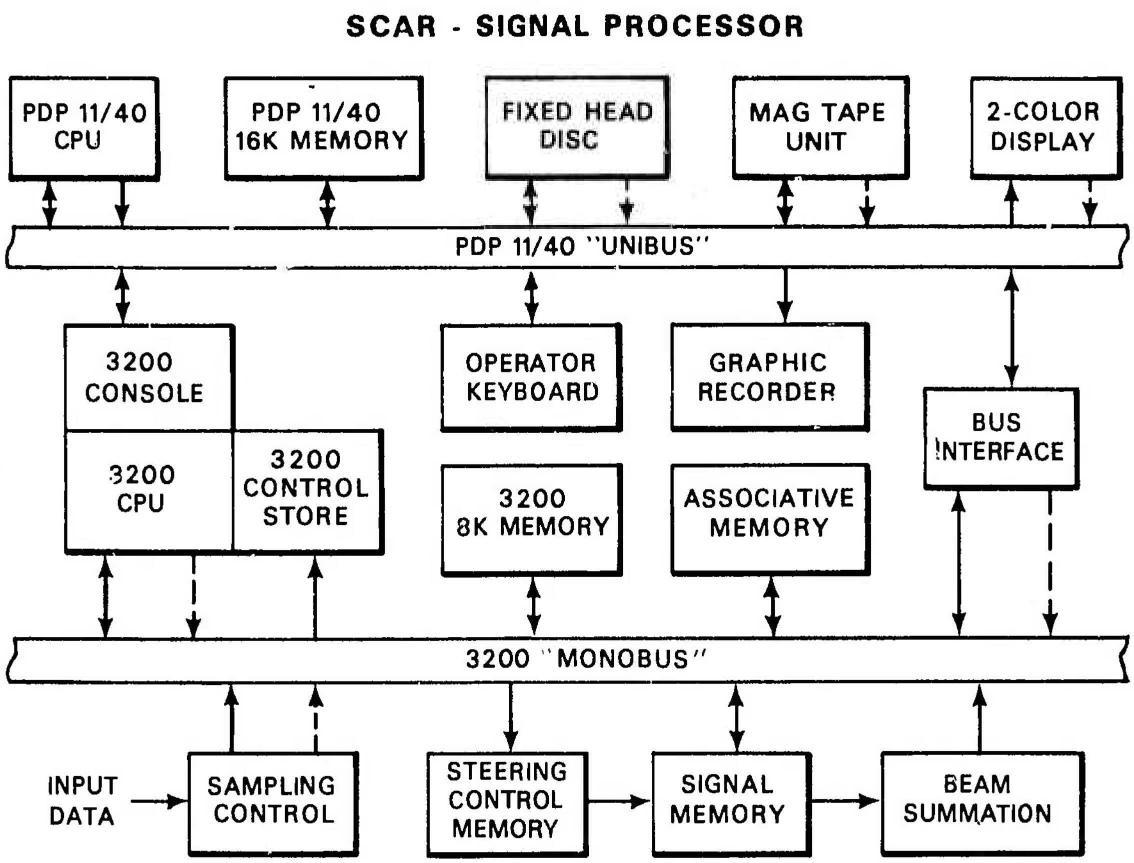


Figure 4. Block diagram showing the relationship of the minicomputer hardware for signal processing.

CONCLUSION

The Scattering Array has been constructed and has been operated at sea. It is an engineering success. The computer software necessary for data reduction is near completion, which will allow us to evaluate the scientific success of the array.

What we intend to observe is the vertical distribution of density features in the thermocline region of the water column, and to observe how this distribution changes over time. Complementary measurements will include a direct water density measurement, sampling of the water current at the array depth, and measurement of wind velocity. The density measurement will provide some ground truth to compare with the acoustic data. The water current measurement will allow an estimate of the horizontal lengths of features as they pass by. Finally, the wind velocity measurement may permit observation of air-sea interaction process and how this alters the density field of the upper ocean.

These are, of course, ambitious goals and this is a complex system with which to attain them. However, it is felt that this is the quantity of data needed to begin to describe and understand the phenomenon we call ocean microstructure.

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